Simulation and Precision Engineering Lead to Extraordinary Results in Experiment

A multidisciplinary international team, led by Livermore physicist Don Roberts, designed and conducted the first subscale integrated weapons experiment in the U.S. since the 1980s. What made this test truly remarkable was that the entire experiment was designed using an advanced, three-dimensional (3D) supercomputer software code.

The Laboratory conducts scores of hydrodynamics experiments, or hydrotests, such as integrated weapons experiments (IWEs), which re-create the exact specifications of a nuclear device except for the special nuclear material. Conducted as part of the Stockpile Stewardship Program, which ensures the safety, security, and reliability of the nation's current weapons stockpile without nuclear testing, IWEs address performance- and safety-related questions and are also used to improve computer simulations.

Hydrotests are set up to understand what happens to metal adjacent to a high-explosive detonation. An experiment involves first detonating insensitive high explosives (IHEs) that surround a pit made of inert (nonfissile) material. Except for the nonfissile materials, experiments use parts and materials similar to those in stockpile devices, including the same high explosives. (See *S&TR*, September 2007, pp. 4–11.)

In the early years of the Laboratory, Livermore conducted hydrotests in a trial-and-error fashion, particularly when new diagnostics were developed. Scientists would design a diagnostic, and if the experiment didn't work, they would modify it and conduct another experiment. As computer simulation power has increased, researchers can better model diagnostic features, thus requiring fewer hydrotests.

Several features of the multimillion-dollar test conducted in October 2011 were extraordinary. First, in preparation for possible follow-on subcritical experiments using special nuclear material, the experiment was done at subscale—that is, at a smaller scale than an actual nuclear device. Second, the experiment included new diagnostics, scaled detonators, and boosters developed specifically for this IWE but that had not been tested. Finally, the experiment required unprecedented precision in the engineering and assembly of the device because of its subscale size.

A key goal of this experiment was to obtain as much information as possible about the continually changing velocities of materials as they implode. Photonic Doppler velocimetry (PDV), a technique invented by Livermore scientists, can measure particle velocities up to 30 kilometers per second, with a precision of 1 meter per second. (See *S&TR*, July/August 2004, pp. 23–25.) The team used PDV to precisely measure the response of the materials to shock waves.

Designing Experiments by Computer

This experiment was ambitious because the device had many original pieces of equipment that were designed to an unprecedented level of precision. Traditionally, any of these design features would have required a number of expensive preparatory experiments to ensure successful data collection.

To avoid the financial costs and schedule delays of preparatory experiments, Roberts assembled a team that included computer-modeling experts who developed 3D simulations that showed the functioning of the experiment from the lighting of the detonators through data collection. Much of the trial-and-error process was accomplished with simulations rather than with a series of expensive—often $5 million—hydrotests.

Still, the accuracy of the simulations was a concern. For example, the team used IHE computer models to simulate the implosion, but devices that use IHE are difficult to model accurately. IHE is more resistant to fire or accident, but it is also harder to detonate than conventional high explosives. The team performed small-scale experiments at Livermore's High Explosives Applications Facility (HEAF) to test the models, which led to improved simulations and a modified design of the detonators. (See *S&TR*, July/August 2012, pp. 4–11 for more information about research and development of explosives, propellants, and pyrotechnics at HEAF.)

All-Optical Probe Dome

Historically, Livermore scientists used pin domes to obtain data about the temporal and spatial uniformity of an implosion. Pin domes, which are small spheres with hundreds of protruding radial pins of different lengths, send signals as the implosion strikes the dome, and the data from each pin reflect a snapshot at that point in space and time.

The Livermore-designed all-optical probe dome is studded with outlets for fiber optical lines. The new diagnostic provided continuous photonic Doppler velocimetry data during a subscale integrated weapons experiment performed at the Laboratory's Contained Firing Facility in October 2011.

In the continual search for better equipment to measure extreme velocities, Roberts's team designed a diagnostic called the all-optical probe dome. The dome is studded with outlets for fiber optical lines leading to recording instruments, and it provides 60 channels of continuous PDV data using both Livermore and National Security Technologies, LLC, multiplexers. An additional 12 channels provide exterior data. (See the related article on p. 14, which describes the R&D 100 Award-winning multiplexers.) Mike Dunning, program director for Livermore's Primary Nuclear Design, says, "The all-optical probe dome provides continuous data versus snapshots—akin to replacing 10 snapshots of a horse race with a full movie. We have much more detailed information about the response of the metal. This hydrotest featured the most PDV channels ever used at the Laboratory."

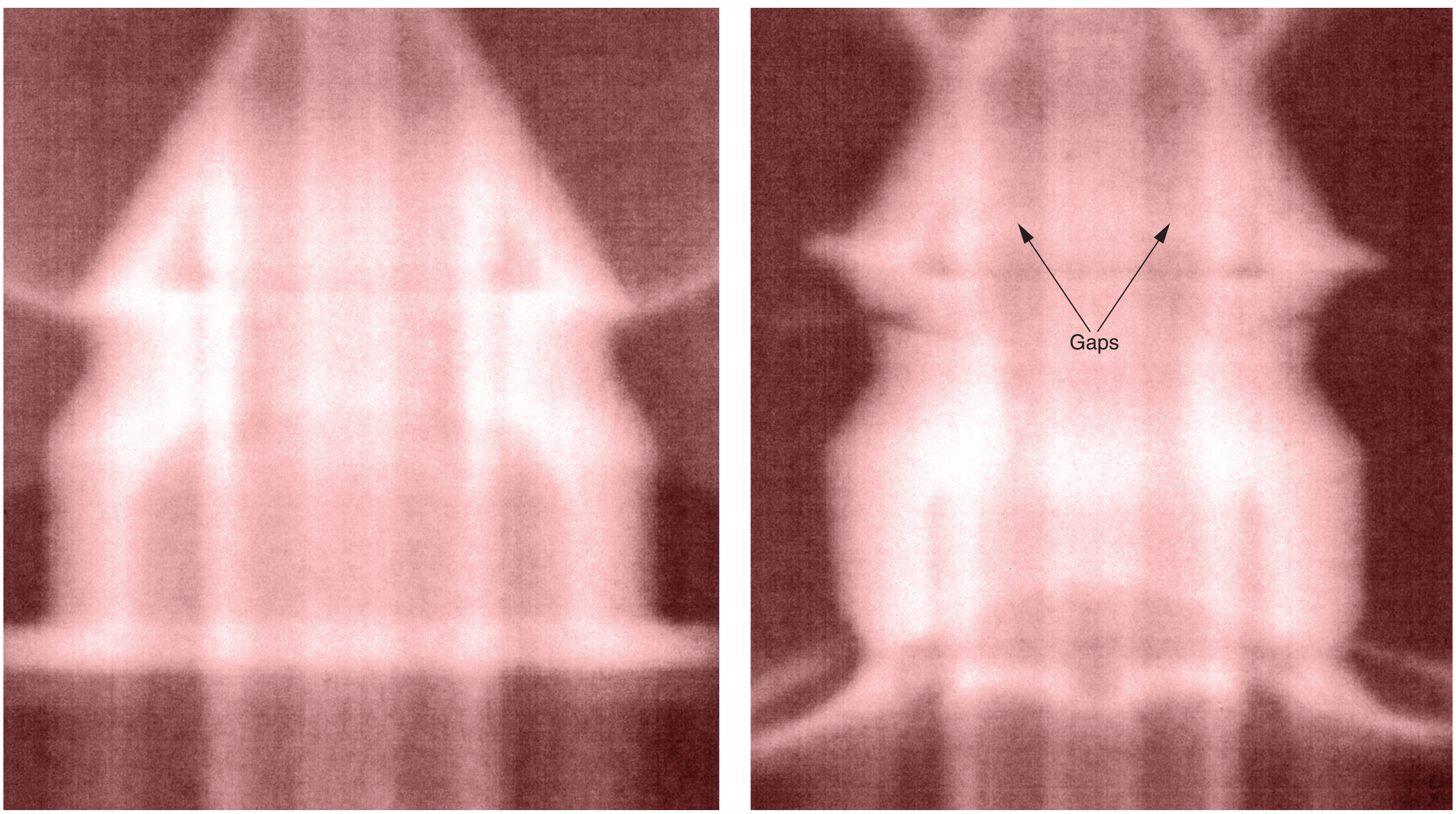
Precision Engineering

Once the experiment was simulated in 3D, the team had to build the device. "The real trick was to capture the available information within the few microseconds before the diagnostics were destroyed by the explosion," says Matt Wraith, Livermore engineering team leader. "All the months or even years of setup go to waste if we don't obtain the data." To prevent the destruction of the probe dome before the data could be captured, former Livermore hydroengineer Ryan Krone designed gaps around each of the fibers, which allowed them to transmit information in the tiny fractions of a second before their destruction by the implosion.

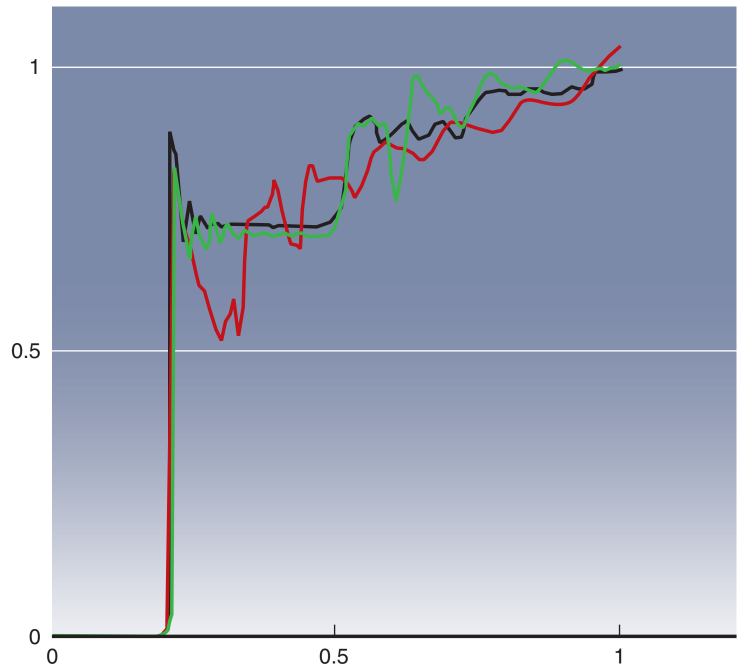
To ensure that the researchers could extract as much data as possible, the engineers, drafter–designers, specialized experimental physicists (called ramrods), and technicians were responsible for building components that matched the simulations exactly. These components required high-precision machining and had to be manufactured to unprecedented tolerances, a task made even more difficult because of the small size of the device.

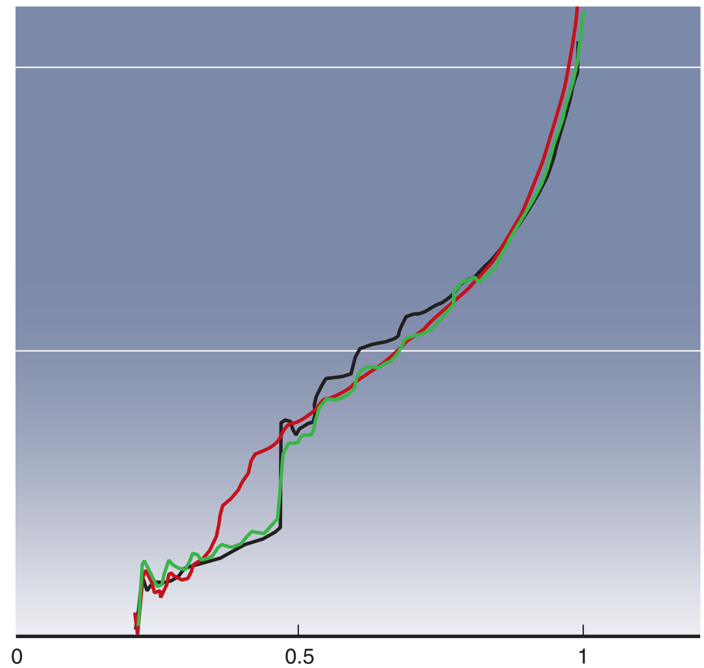
Once the components were fabricated and the parts were carefully inspected, the device had to be assembled at the same level of precision as each individual part had been manufactured. As in watchmaking, it is not enough to just have precise parts—they must be assembled perfectly. The experimental device was even more difficult to assemble than an actual nuclear device because of its small scale. To ensure successful assembly, the team used Livermore's emerging rapid prototyping capability to fabricate practice parts, which were then used to refine assembly techniques. (See *S&TR*, March 2012, pp. 14–20.)

This hydrotest, which was the culmination of three years of work, took place at the Contained Firing Facility (CFF) at the Laboratory's Experimental Test Site located 24 kilometers southeast of Livermore. CFF, the only one of its kind in the Department of Energy complex, allows the Laboratory to conduct nonnuclear high-explosives



Radiographs of the probe dome taken (left) before and (right) during detonation show the central cylinder, which contains optical fibers. The dark lines show the precisely engineered gaps that delay the implosion long enough to allow the optical fibers to send data to the multiplexers located outside the firing chamber.





(left) The original material failure (spallation) model (red line) does not correspond well to the experimental spallation data (black line). The model was then updated (green line) and now corresponds more closely with the experimental data. (right) This postshot model of explosives performance (red line) still fails to capture some features in the experimental data (black line). After the model was improved (green line), the simulation corresponds more closely with the experimental data.

experiments indoors, minimizing noise and reducing the emission of hazardous materials. It provides a controlled environment for experiments to optimize data capture. In addition to the firing chamber, the facility includes a staging area, diagnostic equipment rooms with radiographic capabilities and ports to the firing chamber, and a control room from which the shot is fired.

Results Pay Off

The experimental data help validate computer modeling of test-device performance and support upcoming milestones for predictive capabilities. Results led to improved high-explosives and material failure (spallation) models. (See the figure above.) Simulations now correspond more closely to experimental results.

“Bringing together diverse teams of experts to accomplish our programmatic objectives is a hallmark of this Laboratory,” says Dunning. “In this case, Don assembled a team that spans multiple organizations inside and outside Livermore.” The team included 44 people from the Laboratory, three from the Nevada National Security Site (formerly known as the Nevada Test Site), one from Los Alamos National Laboratory, and six from Great Britain’s Atomic Weapons Establishment. Disciplines encompassed physicists, experimentalists, computer scientists, diagnosticians, engineers, drafter–designers, ramrods, machinists, inspectors, and technicians.

Despite all the innovative technology and the higher level of precision engineering, the team obtained full results with a single high-risk, high-payoff experiment. The high-fidelity, continuous temporal measurements not only provided more information about the actual test but were also used to further improve computer simulation codes.

—*Karen Rath*

Key Words: all-optical probe dome, hydrodynamics experiment, hydrotest, integrated weapons experiment (IWE), multiplexer, photonic Doppler velocimetry (PDV), precision engineering, three-dimensional (3D) computer simulation.

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